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Search for high-mass Zγ resonances in $e^+e^-\gamma$ and $\mu^+\mu^-\gamma$ final states in proton-proton collisions at $\sqrt{s} = 8$ and 13 TeV

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Abstract: This paper describes the search for a high-mass narrow-width scalar particle decaying into a Z boson and a photon. The analysis is performed using proton-proton collision data recorded with the CMS detector at the LHC at center-of-mass energies of 8 and 13 TeV, corresponding to integrated luminosities of 19.7 and 2.7 fb^{-1}, respectively. The Z bosons are reconstructed from opposite-sign electron or muon pairs. No statistically significant deviation from the standard model predictions has been found in the 200–2000 GeV mass range. Upper limits at 95% confidence level have been derived on the product of the scalar particle production cross section and the branching fraction of the Z decaying into electrons or muons, which range from 280 to 20 fb for resonance masses between 200 and 2000 GeV.

Keywords: Beyond Standard Model, Hadron-Hadron scattering (experiments)

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1 Introduction

The ATLAS and CMS experiments have observed [1–3] a standard model (SM) like Higgs boson at 125 GeV [4]. While this discovery has reaffirmed the SM, it is widely believed that the SM is a low-energy approximation of a more complex theory [5]. An enhancement with respect to the SM in the rate of rare decays of the 125 GeV boson or the discovery of additional scalar or pseudoscalar bosons would provide evidence that this is the case. Searches for the rare decay of the 125 GeV Higgs boson into a Z boson and a photon have been conducted by both ATLAS and CMS [6, 7], but have insufficient sensitivity to probe the SM Higgs boson hypothesis.

In the context of the wider search for new resonances in the diphoton final state [8–10], information from the $Z\gamma$ channel provides important complementary information. For example, an extended SM incorporating a scalar (or pseudoscalar) decaying to two photons would imply that $Z\gamma$ decays should be observed as well [11].

We present the results for a search for a high-mass scalar, X, with mass between 200 GeV and 2 TeV, decaying to $Z\gamma$. The analysis is performed by studying proton-proton collisions recorded with the CMS detector at the CERN LHC. The analyzed data samples correspond to integrated luminosities of 19.7 and 2.7 fb^{-1}, recorded at center-of-mass energies of 8 and 13 TeV, respectively. The search is for localized excesses in the $X \to Z\gamma$ channel, with the Z boson identified by means of its decays into an electron or a muon pair. The dominant backgrounds consist of the irreducible contribution from the continuum $Z\gamma$ production and the reducible backgrounds from either final-state radiation in Z boson decays or Z boson production in association with one or more jets (Z plus jets), where a jet is misidentified as a photon. The background is determined directly from data. Searches for a scalar singlet decaying to $Z\gamma$ have been performed at the LHC by ATLAS at center-of-mass energies of 8 [12] and 13 TeV [13].

2 The CMS detector

A detailed description of the CMS detector, together with the definition of the coordinate system used and the relevant kinematic variables, can be found elsewhere [14]. The central feature of the CMS apparatus is a superconducting solenoid, 13 m in length and 6 m in diameter, which provides an axial magnetic field of 3.8 T. Within the field volume there are several particle detection systems. Charged-particle trajectories are measured by silicon pixel and strip trackers, covering $0 < \phi < 2\pi$ in azimuth and $|\eta| < 2.5$ in pseudorapidity. A lead tungstate crystal electromagnetic calorimeter (ECAL) is partitioned into a barrel region with $|\eta| < 1.48$ and two endcaps that extend up to $|\eta| = 3$. A brass and scintillator hadron calorimeter surrounds the ECAL volume and covers the region $|\eta| < 3$. Iron forward calorimeters with quartz fibers, read out by photomultipliers, extend the calorimeter coverage up to $|\eta| = 5$. The calorimeters provide measurements of the energy of photons, electrons, and hadronic jets. Lead and silicon-strip preshower detectors are located in front of the endcap electromagnetic calorimeter. Muons are identified and measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. The detector is nearly hermetic, allowing energy balance measurements in the plane transverse to the beam direction. A two-tier trigger system selects proton-proton collision events of interest.

3 Particle reconstruction and event selection

The selected events are required to pass a dielectron trigger, which has transverse momentum, p_{T}, thresholds of 17 and 12 GeV, respectively, on the two electrons, or a dimuon trigger, with thresholds of 17 and 8 GeV on the two muons. The analysis of the 13 TeV data also makes use of trigger paths that require the presence of only one muon, with a transverse momentum threshold of 20 GeV. The trigger efficiencies for events containing two leptons satisfying the subsequent event selection requirements are measured to be between 90% and 98% for the $e^+e^-\gamma$ channel depending on the electron transverse momenta, and about 91% for the $\mu^+\mu^-\gamma$ channel. These efficiencies are determined with a data sample enriched in Z boson events.

Events with two opposite-sign, same-flavor leptons (electrons or muons) and a photon are selected. All particles are required to be isolated, and the lepton with the highest p_{T} is required to satisfy $p_{\mathrm{T}} > 20\,(25)$ GeV in the analysis of 8 (13) TeV data, while the second-leading lepton must have $p_{\mathrm{T}} > 10\,(20)$ GeV. The photon is required to satisfy $p_{\mathrm{T}} > 40$ GeV. The electrons and photon must have $|\eta| < 2.5$, while the muons must have $|\eta| < 2.4$. Photons and electrons in the ECAL barrel-endcap transition region $1.44 < |\eta| < 1.57$ of the electromagnetic calorimeter are excluded. More details on reconstruction of photons, electrons, and muons can be found in refs. [15–17].

Events are required to have at least one vertex [18], with the reconstructed longitudinal position within 24 cm of the geometric center of the detector and the transverse position within 2 cm of the beam interaction region. There are multiple reconstructed vertices associated with additional interactions (pileup), and the vertex with the highest sum of the p_T^2 of its associated tracks is chosen as the primary vertex. The leptons are required to originate from the same primary vertex by requiring, for each track, that its transverse impact parameter with respect to the primary vertex is smaller than 2 mm and that its longitudinal impact parameter is smaller than 2 (5) mm for electrons (muons).

The observables used in the photon selection are as follows: isolation variables based on a particle-flow (PF) algorithm [19, 20], kinematic variables corresponding to the location and energy of the photon, shower shape variables that provide information on the size and shape of the energy deposition in the ECAL, and a variable taking into account the energy deposited by pileup interactions, calculated with the FastJet package [21]. Identification and isolation requirements in the analysis of the 8 TeV data are enforced through the use of a multivariate discriminant, whereas simple, cut-based selection is used in the analysis of 13 TeV data. The search conducted in 8 TeV data targets a lower mass range, so the photon identification criteria with the most efficient rejection of the jet-induced background were chosen.

Photon candidates are rejected if a cluster of hits in the tracker pixel detector is found to be compatible with the ECAL energy cluster position. The efficiency of the photon identification is measured from $Z \to ee$ data [22] by treating the electrons as photons [3], and is found to be 90% for photons with $p_T > 40$ GeV. These efficiencies include the losses due to photon conversions caused by the pixel tracker veto requirement, estimated with $Z \to \mu\mu\gamma$ events, where the photon is produced via final-state radiation.

Isolation requirements are based on objects reconstructed with the PF algorithm within $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$ from the photon candidate direction, where $\Delta\eta$ and $\Delta\phi$ are, respectively, the differences in the pseudorapidity and azimuth angles between the photon and the given reconstructed object. Only charged candidates are considered in the enforcement of isolation criteria in the analysis of 13 TeV data, whereas additional photons are also considered in the analysis of 8 TeV data.

Electron candidates are reconstructed as clusters of energy deposits in the ECAL matched to signals in the silicon tracker [16]. The electron energy resolution is improved by using a multivariate regression technique resulting in improvements of 10 and 30% in the mass resolution for $Z \to ee$ events over the standard CMS electron reconstruction in the barrel and endcap calorimeters, respectively [16]. Electrons are identified via loose requirements on the shape of these energy deposits, on the ratio of energies in associated hadron and electromagnetic calorimeter cells, on the geometrical matching between the energy deposits and the associated track, and on the consistency between the energy reconstructed from the calorimeter deposits and the momentum measured in the tracker. The electron selection criteria used in the analysis of 8 TeV data are optimized further for background rejection using a multivariate approach. The training of the multivariate electron reconstruction is performed using simulated events, while the performance is validated using data.

Muon candidates [17] are reconstructed from tracks found in the muon system that are associated with the tracks in the silicon detectors. Muon identification criteria are based on the quality of the track fit and the number of associated energy deposits in the pixel and strip tracking detectors. The total efficiencies for the combined muon identification and pileup-corrected isolation criteria are better than 95%.

Electrons and muons from Z boson decays are expected to be isolated from other particles. A fixed cone of size $\Delta R = 0.4$ is constructed around the direction of each lepton candidate in the search performed in 8 TeV data, while ΔR varies with the lepton p_{T} in the selection used in the analysis of 13 TeV data according to the relation:

$$\Delta R = \begin{cases} 0.2, & p_{\mathrm{T}} < 50\,\mathrm{GeV} \\ \frac{10\,\mathrm{GeV}}{p_{\mathrm{T}}}, & 50 < p_{\mathrm{T}} < 200\,\mathrm{GeV} \\ 0.05, & p_{\mathrm{T}} > 200\,\mathrm{GeV}. \end{cases} \tag{3.1}$$

This ensures high lepton identification efficiency even for highly-boosted Z boson decays, as expected in the decay of high-mass resonances. The relative isolation of the lepton is quantified by summing the transverse momenta of the relevant PF candidates within this cone, excluding the lepton itself. To account for the contamination from pileup interactions, charged particles originating from additional vertices are excluded from the estimate, and a correction is applied to account for the neutral PF objects originating from pileup activity, which cannot be excluded by vertex identification. The resulting quantity, divided by the lepton transverse momentum, is required to be less than 0.4 for both electrons and muons in the analysis of 8 TeV data, and less than 0.1 (0.2) for electrons (muons) in 13 TeV data. This requirement rejects misidentified leptons and background arising from hadronic jets. Finally, the separation between each lepton and the photon must satisfy $\Delta R > 0.4$ in order to reject events with final-state radiation.

The invariant mass of the dilepton system is required to be greater than 50 GeV. In the selection used in 8 TeV data, no upper dilepton mass condition is needed, while in the selection used in 13 TeV data the dilepton mass is required to be below 130 GeV. The minimum dilepton mass requirement rejects contributions from pp $\to \gamma\gamma^*$, where an internal conversion of the photon produces a dilepton pair. In the rare cases where more than one dilepton pair is present, the one with an invariant mass closest to the Z boson mass is taken. The final set of requirements combines the information from the photon and the leptons: (i) the invariant mass $M_{\ell\ell\gamma}$ of the $\ell^+\ell^-\gamma$ system (where $\ell = \mathrm{e}, \mu$), is required to be above 150 (200) GeV in the analysis of 8 (13) TeV data; and (ii) the ratio of the photon transverse energy to $M_{\ell\ell\gamma}$ must be greater than 0.27. This latter requirement suppresses backgrounds due to misidentification of photons, without significant loss in signal sensitivity and without introducing a bias in the $M_{\ell\ell\gamma}$ spectrum.

4 Background modelling

Simulations indicate that 80–90% of the background after the full event selection is due to SM Zγ production with initial-state radiation, with the remainder mostly due to the

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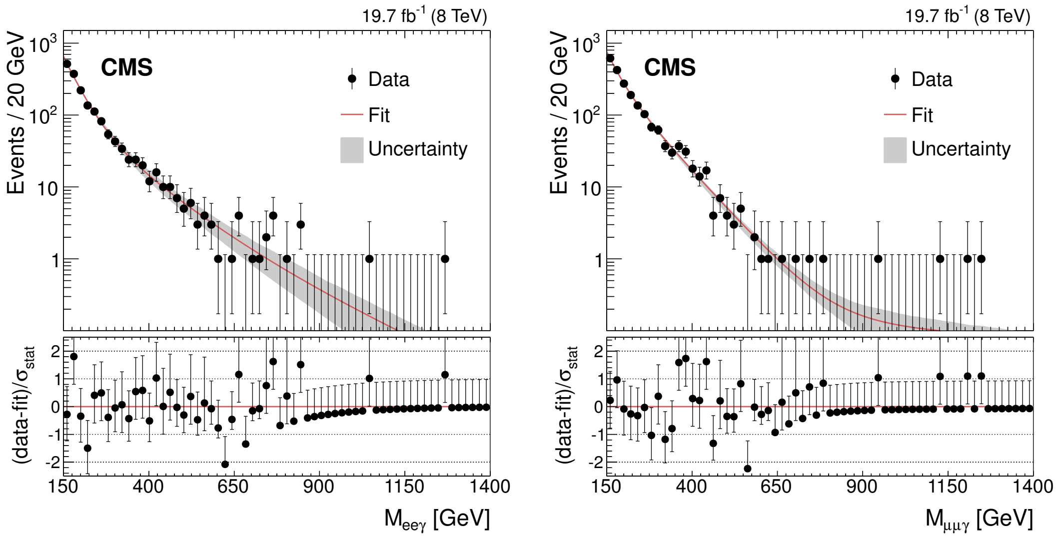

Figure 1. Observed $M_{\ell\ell\gamma}$ invariant mass spectra in the 8 TeV data, for the $e^+e^-\gamma$ (left) and the $\mu^+\mu^-\gamma$ (right) channels. The fitted function is represented by a line, with the 68% uncertainty band as grey shading. The lower panels show the difference between the data and the fit, divided by the uncertainty σ_{stat}, that includes the statistical uncertainty in both the data and the fit. For bins with a low number of data entries, the error bars correspond to the Garwood confidence intervals.

contribution from Z plus jet events, where the jet is misreconstructed as a photon. The $M_{\ell\ell\gamma}$ distributions are steeply and smoothly falling with increasing mass. The background is measured directly in the data, through an unbinned maximum-likelihood fit to the observed $M_{\ell\ell\gamma}$ distributions, separately in the $e^+e^-\gamma$ and $\mu^+\mu^-\gamma$ channels. The background is parametrized with empirical formulae.

In the 8 TeV analysis the background shape is parameterized with the sum of three exponential decay functions. The fit is performed for values of $M_{\ell\ell\gamma} > 150\,\text{GeV}$. The potential bias in the background measurement is studied by using pseudo-data generated from different functional forms and fitted with the function under test. The results of these fits are used to determine an appropriate model for the background, such that the bias introduced in the signal measurement is smaller than 1/5 of the statistical uncertainty in its determination. The chosen model (sum of three exponential decay functions) is found to satisfy this criterion across the search mass range. The observed $M_{\ell\ell\gamma}$ invariant mass spectra in 8 TeV data are shown in figure 1. The results of the fit is represented by a line, with the 68% uncertainty band as grey shading.

The 13 TeV search employs a strategy similar to the 8 TeV search. The fit is performed for values of $M_{\ell\ell\gamma} > 200\,\text{GeV}$. The function chosen for the background estimate,

$$f(x) = x^{a+b\log x}, \tag{4.1}$$

describes the background shape well and does not create a significant bias. The absence of significant bias has been verified by fitting a large number of pseudo-datasets generated from various background models, and measuring the difference between the true and fitted background yields in different $M_{\ell\ell\gamma}$ windows; in each window a pull variable is defined as

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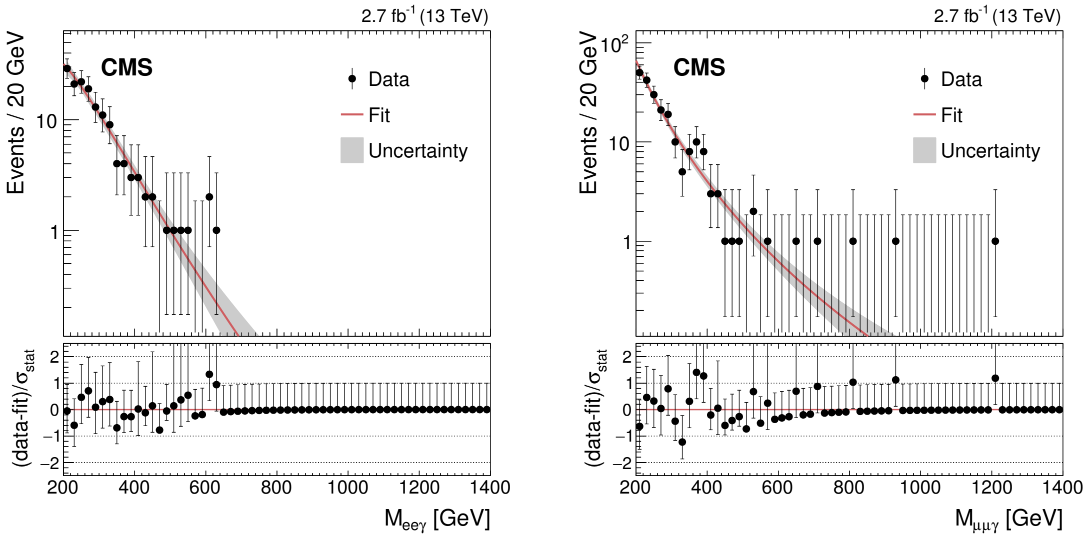

Figure 2. Observed $M_{\ell\ell\gamma}$ invariant mass spectra in the 13 TeV data, for the $e^+e^-\gamma$ (left) and the $\mu^+\mu^-\gamma$ (right) channels. The fitted function is represented by a line, with the 68% uncertainty band as gray shading. The lower panels show the difference between the data and the fit, divided by the uncertainty σ_{stat}, which includes the statistical uncertainty in both the data and the fit. For bins with a low number of data entries, the error bars correspond to the Garwood confidence intervals.

the difference between the true and fitted yields, divided by the statistical uncertainty. If the absolute value of the median of this distribution is found to be above 0.5 in an interval, an additional uncertainty is assigned to the background parametrization. A modified pull distribution is then constructed, increasing the statistical uncertainty in the fit by an extra term, denoted the *bias term*. The bias term is parametrized as a smooth function of $M_{\ell\ell\gamma}$, which is tuned in such a manner that the absolute value of the median of the modified pull distribution is less than 0.5 in all intervals. This additional uncertainty is included in the likelihood function by adding to the background model a component having the same shape as the signal, with a normalization coefficient distributed as a Gaussian of mean zero, and with a width equal to the integral of the bias term. This inclusion of the additional component takes into account the possible mismodeling of the background shape. The bias term which is used in this analysis amounts to about 5×10^{-3} events/GeV at $M_{\ell\ell\gamma} = 600$ GeV, and smoothly falls to about 5×10^{-4} events/GeV around $M_{\ell\ell\gamma} = 2$ TeV.

The observed $M_{\ell\ell\gamma}$ invariant mass spectra in 13 TeV data are shown in figure 2, for the $e^+e^-\gamma$ (left) and $\mu^+\mu^-\gamma$ (right) channels. The results of the fit and its uncertainty are shown with a line and a band.

No events with invariant mass larger than 1275 (1220) GeV pass the selection on 8 (13) TeV data.

5 Signal modeling

We focus on narrow-width signal models, where the intrinsic width of the resonance is negligible compared to the experimental resolution. Scalar resonances decaying to $Z\gamma$ are generated at leading order with PYTHIA 8.175 [23] and NNPDF2.3 [24] parton distribution functions (PDF). The 8 TeV generator uses the Z2* tune [25] to describe the underlying event and the 13 TeV generator, the CUETP8M tune [26]. Several samples are generated with masses ranging from 200 (350) GeV to 1.2 (2) TeV, in the 8 (13) TeV analysis. The search performed in 13 TeV data begins at higher invariant mass in order to avoid the region where the background is sculpted by the kinematic selections imposed on the final-state objects. As far as the upper range, the analysis of the 8 TeV data ends where the results based on the 13 TeV analysis dominate the combination.

The signal distribution in $M_{\ell\ell\gamma}$ is obtained from the generated events that pass the full selection. The signal shape is parametrized with empirical functions; the function chosen is the sum of a Gaussian and Crystal Ball function ([27], see appendix D) for the 8 TeV analysis, and an extended form of the Crystal Ball function, with a Gaussian core and two power-law tails, for the 13 TeV analysis. The fitted parameters are determined from the simulated samples at each mass point, separately for the electron and muon channels, and then interpolated through polynomial fits to generic $M_{\ell\ell\gamma}$ values in order to have smoothly varying signal shape parametrizations. The typical mass resolution for signal events is 1% for the $e^+e^-\gamma$ channel and 1–2% for the $\mu^+\mu^-\gamma$ channel, depending on the mass of the resonance.

The product of the expected signal acceptance and efficiency in the analysis of 8 TeV data rises from about 33% at $M_{\ell\ell\gamma} = 200$ GeV to about 45% at $M_{\ell\ell\gamma} = 1.2$ TeV. In the analysis of 13 TeV data it rises from about 25% (35%) at $M_{\ell\ell\gamma} = 350$ GeV to about 45% (55%) at $M_{\ell\ell\gamma} = 2$ TeV, for the $e^+e^-\gamma$ ($\mu^+\mu^-\gamma$) channel.

6 Systematic uncertainties

The background spectra are described by parametric functions of $M_{\ell\ell\gamma}$. The coefficients are obtained from a fit to the data events, and considered as unconstrained nuisance parameters in the fit. Thus the description of the background is derived from data. No systematic uncertainty related to the background description is considered, as possible biases are accounted for in the bias terms.

The systematic uncertainty in the signal description arises from the integrated luminosity measurement [28, 29], the trigger efficiency, the effect on the signal acceptance from the choice of parton distribution functions [30], the imperfect simulation of the lepton and photon efficiencies, and the signal mass scale and resolution. These uncertainties have been evaluated separately at 8 and 13 TeV, and their magnitudes are summarized in table 1. The photon efficiency uncertainty of the 13 TeV data analysis is larger because of the use of preliminary calibrations. The sources of uncertainty are considered to be completely uncorrelated between the two center-of-mass energies.

7 Results

No significant excess is observed with respect to the SM background predictions. Upper limits are set on the production cross section of high-mass scalar resonances using the

Source	8 TeV	13 TeV
Integrated luminosity	2.6%	2.7%
PDF choice	1%	1%
Trigger efficiency (ee, $\mu\mu$)	3%, 2%	3%, 2%
Lepton efficiency	5%	5%
Photon efficiency	1–2.6%	5%
Mass scale and resolution (eeγ, $\mu\mu\gamma$)	1%, 1–10%	1%, 1–5%
Total systematic uncertainty (eeγ, $\mu\mu\gamma$)	6.6–7.0%, 6.2–12%	8.3%, 8.3–9.6%

Table 1. Summary of considered systematic uncertainties in signal.

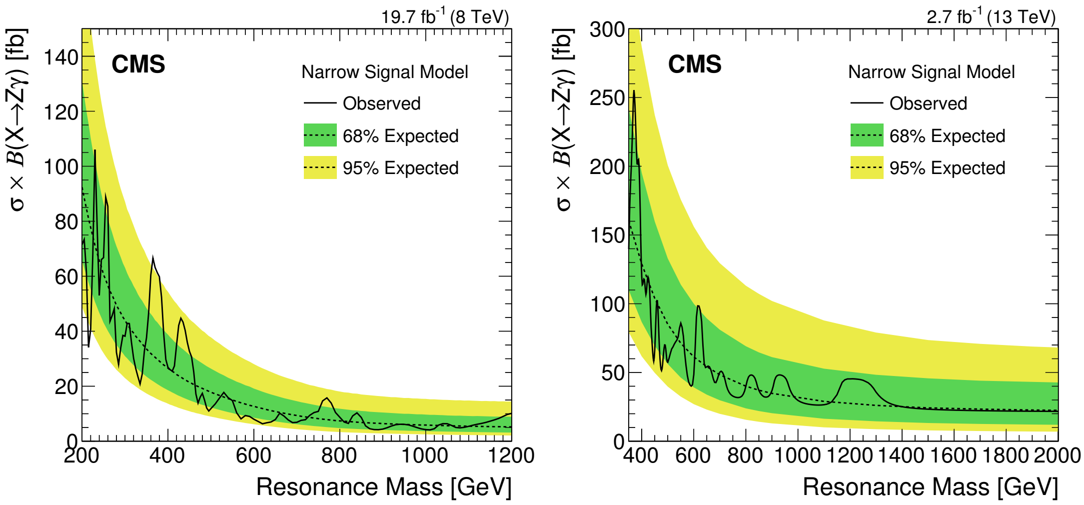

Figure 3. Expected and observed upper limits, at 95% CL, on the cross section times branching fraction for X $\rightarrow$ Zγ obtained with the searches performed at 8 TeV (left) and at 13 TeV (right).

modified frequentist method, commonly known as CL$_s$ [31, 32]. An example of its usage is found in [2]. Asymptotic formulae [33] are used in the calculation. The individual expected and observed upper limits at 95% confidence level (CL) on the product of the cross section and the branching fraction for X $\rightarrow$ Zγ are shown in figure 3.

The combination of the two results accounts for the different parton luminosities for collisions at 8 and 13 TeV, which have been calculated with the NNPDF2.3 parton distributions [24]. The effect of using different PDFs for the scaling has been evaluated and affects the limits by at most a few percent, mainly in the low-mass region. The signal is assumed to be produced solely through gluon-gluon fusion, and the 8 TeV limit is scaled up by the corresponding parton luminosity ratio, which ranges between 3 and 7 in the 0.2 to 1.2 TeV mass region, and is about 4.3 for a signal with a mass of 750 GeV.

Figure 4 (left) shows the 95% CL upper limits on the 13 TeV cross section, $\sigma_{13\,\mathrm{TeV}}(\mathrm{X} \rightarrow \mathrm{Z}\gamma)$, as a function of the resonance mass, for the 8 TeV (blue, lighter) and 13 TeV (red, darker) analyses, and their combination (black). The expected (observed) limits are shown as dashed (solid) lines. Figure 4 (right) shows the combined 8 and 13 TeV limit with its 68% (inner green) and 95% (outer yellow) uncertainty bands. The discontinuities in the limits are an artifact of the different ranges exploited by the two searches.

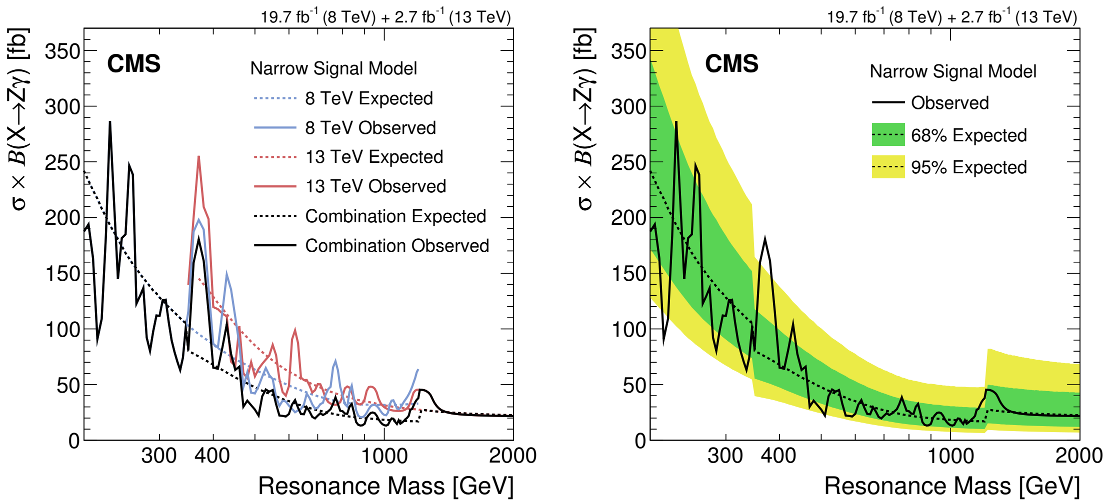

Figure 4. Left: expected and observed upper limits, at 95% CL, on the 13 TeV cross section $\sigma_{13\,\mathrm{TeV}}(\mathrm{X} \to \mathrm{Z}\gamma)$ for the scaled 8 TeV (blue, lighter) and 13 TeV (red, darker) searches, together with their combination (black). Expected limits are shown with dashed lines, observed ones with solid lines. Right: 95% CL upper limit for the combination of 8 TeV and 13 TeV data. The solid (dashed) line represents the observed (expected) limit, whereas the inner green (outer yellow) bands represent the 68% (95%) uncertainty bands.

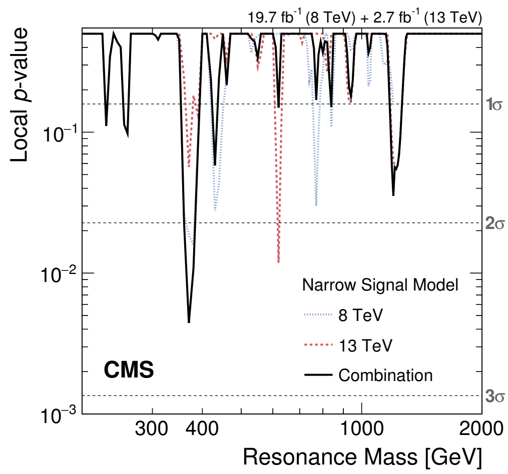

Figure 5. Observed background-only local p-values for the scaled 8 TeV search (blue, dotted), the 13 TeV search (red, dashed), and the combination (black, solid).

Background-only local p-values are defined as the probability of obtaining, under the background-only hypothesis, a result equal or larger than the one observed in the data. Figure 5 shows the observed background-only p-values for the 8 TeV search (blue, dotted), the 13 TeV search (red, dashed), and their combination (black). The fluctuation at $M_{\ell\ell\gamma} \approx$ 370 GeV corresponds to a local significance of 2.6 σ, and a global significance smaller than one standard deviation, once the 'look-elsewhere' effect has been taken into account [34]. This has been computed by counting the fraction of times the background-only p-value crosses the level corresponding to 0.5 standard deviations in the full mass range in which limits are set.

8 Summary

A search for heavy resonances decaying to $Z\gamma$, with further decay $Z \to \ell^+\ell^-$, with $\ell = e$ or μ, has been presented. The search makes use of proton-proton data collected by the CMS detector at the LHC, corresponding to integrated luminosities of 19.7 and $2.7\,\mathrm{fb}^{-1}$ at 8 and 13 TeV, respectively. The background is measured directly from data and localized excesses are looked for. No significant deviation with respect to the standard model expectation is found. Upper limits at 95% confidence level are set on the production cross section of narrow resonances, ranging from 280 to 20 fb for resonance masses from 200 to 2000 GeV.

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